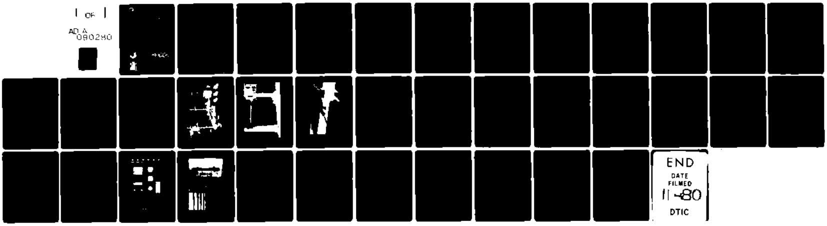
AD-A090 280   ACUREX CORP MOUNTAIN VIEW CA ENERGY AND ENVIRONMENTAL DIV   F/G 14/2
AN AUTOMATIC ISOKINETIC SAMPLER FOR PARTICULATE EMISSIONS FROM --ETC(U)
JAN 80 H DEHNE   N00123-75-C-1075
UNCLASSIFIED   ACUREX-78-315   AFESC/ESL-TR-80-04   NL

1 OF 1
AD A
090280



ESL-TR-80-04
(AFESO-161-01-80)

AN AUTOMATIC ISOKINETIC SAMPLER FOR PARTICULATE EMISSIONS FROM AIRCRAFT GAS TURBINE ENGINES

HANS-JOACHIM DEHNE
ACUREX CORPORATION
485 CLYDE AVENUE
MOUNTAIN VIEW, CALIFORNIA 94042

JANUARY 1980

FINAL REPORT
FEBUARY 1975 – JUNE 1978

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

AIR FORCE ENGINEERING AND SERVICES CENTER

AFESC

ENGINEERING AND SERVICES LABORATORY
AIR FORCE ENGINEERING AND SERVICES CENTER
TYNDALL AIR FORCE BASE, FLORIDA 32403

NOTICE

Please do not request copies of this report from HQ AFESC/RD (Engineering and Services Laboratory). Additional copies may be purchased from:

National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

Federal Government agencies and their contractors registered with Defense Technical Information Center should direct requests for copies of this report to:

Defense Technical Information Center
Cameron Station
Alexandria, Virginia 22314

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) (14) ACUREX-78-315

(19)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER ESL-TR-80-04 (AESO 161-01-80)	2. GOVT ACCESSION NO. AD-A090280	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) AN AUTOMATIC ISOKINETIC SAMPLER FOR PARTICULATE EMISSIONS FROM AIRCRAFT GAS TURBINE ENGINES.		5. TYPE OF REPORT & PERIOD COVERED (9) Final Report. Feb[redacted]75-Jun[redacted]78 6. PERFORMING ORG. REPORT NUMBER 78-315
7. AUTHOR(s) (10) Hans-Joachim Dehne		8. CONTRACT OR GRANT NUMBER(s) (15) N00123-75-C-1075
9. PERFORMING ORGANIZATION NAME AND ADDRESS Acurex Corporation Energy and Environmental Division 485 Clyde Avenue, Mountain View, California 94042		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS PE: 62601F JON: 1900-2A-11
11. CONTROLLING OFFICE NAME AND ADDRESS HQ AFESC/RDVC Tyndall AFB, Florida 32403 (16) 1900		12. REPORT DATE (11) Jan[redacted]980 13. NUMBER OF PAGES 35
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) NARF Code 64240 NAS North Island San Diego, California 92135 (12) 37		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

(18) AFESC

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This work was jointly funded by the Air Force Engineering and Services Center (AFESC) Tyndall AFB, Florida and the Naval Air Rework Facility (NARF), NAS, North Island, San Diego, California. The Naval Regional Procurement Office, Long Beach, California was the contracting office. Copies are available

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Isokinetic sampling	Air pollution
Particulate sampling	Turbine engines
Sonic flow	Aircraft
Supersonic flow	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An automated isokinetic sampler for evaluating particulate emissions from aircraft gas turbine engines was designed, constructed and tested. The sampler is capable of collecting the particulate mass emitted by an aircraft gas turbine at the exit plane (non-afterburner operation) for gravimetric measurement and permits simultaneous on-line particle size distribution measurements to be performed.

The particulate is collected on a fiber glass filter for gravimetric

DD FORM 1 JAN 73 1473

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

18. SUPPLEMENTARY NOTES (concluded)

from the National Technical Information Service, Springfield, Virginia 22151.

20. ABSTRACT (concluded)

measurement. The size distribution is determined by conditioning the gas turbine exhaust gases and passing them through a mobility particulate size distribution analyzer.

The sampler has two-axis traverse capability and a maximum sampling capability of 226 l/min (8 scfm). Test data are automatically recorded. Control of the sampler is by means of 12-bit microprocessor.

Preliminary tests were performed at the Naval Air Rework Facility, Alameda, California, at various construction stages of the sampler to evaluate its performance and to measure the effects of fuel additives on particulate emissions on a TF41 gas turbine engine.

PREFACE

This report summarizes work done between February 1975 and June 1978 under Navy contract number N00123-75-C-1075. Hans J. Dehne of Acurex Corporation, 485 Clyde Avenue, Mountain View, California 94042 was the principal investigator. The work was jointly sponsored by the Aircraft Environmental Support Office (AESO), Naval Air Rework Facility (NAVAIREWORKFAC), Code 64240, NAS North Island, San Diego, California 92135 and the Environics Division (RDV), Engineering and Services Laboratory (ESL), Air Force Engineering and Services Center (AFESC), Tyndall AFB, Florida 32403. The AESO project officer was Mr. Larry Michalec.

The report describes the design, construction and preliminary test of an automated isokinetic sampler for particulate emissions from aircraft gas turbine engines. The sampler is now installed in a jet engine test cell at NAS North Island where it will undergo further evaluation and will be employed in Navy and Air Force sponsored environmental engineering studies.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

Joseph A. Martone

JOSEPH A. MARTONE, Maj, USAF, BSC
Project Engineer

Michael G. MacNaughton

MICHAEL G. MACNAUGHTON, LtCol, USAF
Chief, Environmental Sciences Branch

Emil C. Frein

EMIL C. FREIN, Lt Col, USAF
Chief, Environics Division

Robert E. Brandon

ROBERT E. BRANDON
Dep Dir, Engineering & Services Laboratory

(The reverse of this page is blank)

A

TABLE OF CONTENTS

LIST OF FIGURES

SECTION I

INTRODUCTION

There is no generally accepted method for sampling aircraft turbine engine exhaust for the purpose of determining particle mass concentration and size distribution. The difficulty of applying existing particulate sampling equipment, including standard Environmental Protection Agency (EPA) Method 5 apparatus (Reference 1) to aircraft turbine engine exhaust is best described by the Coordinating Research Council (Reference 2). Accordingly, the objective of this joint Navy and Air Force development effort was to design, construct and test a particulate sampler that would operate in the harsh environment encountered at the exit of a turbine engine yet retain the conceptual features of EPA Method 5 (Reference 1) which is the EPA specified method for many industrial sources of particulate. The sampler was designed to measure the mass concentration of emitted particulates and to provide real time data on particle size in engine operating modes from idle to takeoff.

There are several important reasons for sampling turbine engine particulate emissions. Aircraft turbine engines when mounted in fixed test cell facilities are considered in some states to be stationary sources and must meet applicable emission standards. Therefore, compliance testing may be required. Aircraft engine particulate emission factors are needed for air quality evaluations. Currently, particulate emissions are estimated using a correlation developed from limited data which relates engine smoke number to mass emissions (Reference 3). Additional data to verify the correlation, especially at low engine smoke numbers, are needed.

Direct measurement of engine particulate mass emissions and particle size is also required to evaluate smoke suppressant fuel additives, to determine the sooting characteristics of future aviation fuels, to predict the optical properties of engine exhaust plumes, and to provide design criteria for novel approaches to control particulates from engine test cells.

Although the principle of sample collection and measurement was retained, several factors inherent to sampling gas turbine engines demanded major redesign of EPA Method 5 equipment. For example, conventional EPA Method 5 samplers would require up to four hours to collect sufficient mass for accurate gravimetric analysis (i.e., at least 100 milligrams) given the sampling rate of commercially available samplers. Aircraft gas turbine engine tests, however, are short in duration, and testing for long periods is precluded by high cost and the risk of overheating the engine. Further complicating the use of commercially available equipment is the high temperatures and velocities encountered at the exit plane of gas turbine engines, the rapid changes in operating conditions, and the severe noise environment in the test cell.

To overcome the shortcomings of existing EPA Method 5 equipment for application to aircraft turbine engines, the sampler developed in this

program permits both subsonic and supersonic isokinetic sampling and is equipped with additional active cooling capacity for high sampling rates. The sampler is compatible with a variety of test cell configurations and allows remote operation to ensure personnel safety.

A key feature of the sampler is the unique, two-axis traversing stand which permits isokinetic sampling virtually anywhere in the engine exit plane. The stand itself is designed to withstand the high dynamic loads encountered during supersonic sampling. Finally, unlike Method 5 samplers, the system is capable of particle size distribution measurement.

The following sections report on the design goals, design methodology, equipment construction, testing, and conclusions.

SECTION II

DESIGN AND CONSTRUCTION

BACKGROUND

The program objective was to develop a gas turbine engine particulate sampler that was conceptually equivalent to the EPA Method 5 procedure used to measure particulate emissions from stationary sources (Reference 1). Previously, Acurex Corporation under EPA contract developed a high volume Method 5 type sampler that samples particulate at almost ten times the rate of conventional Method 5 sampler (Reference 4). Since this sampler closely approximated the type of system needed in this program, it formed the basis for the design effort.

The system schematic of a Method 5 sampler is shown in Figure 1. The gas to be sampled for particulate concentrations is withdrawn isokinetically from the exhaust stream, passed through the nozzle into the heated probe, and into a filter that is located in an oven maintained at 394°K (250°F). Particulate is collected on fiber glass filters for gravimetric measurement. The sample gas passes from the filter to a set of impingers cooled in an ice bath for condensation of water vapors and other condensible products in the gas stream. The water collected in the impingers is measured to determine the moisture content in the exhaust stream. From the impingers the gas flows through the sampling tube and sampling pump to the control unit for dry gas metering. The control unit also provides readouts and valves to adjust the sampling rate to achieve isokinetic conditions.

DESIGN SPECIFICATIONS

The design goals for the automatic isokinetic aircraft gas turbine particulate sampler called for the adaptation of the Method 5 sampler, as much as feasible, giving due consideration to the severe environmental operating conditions. Typical aircraft gas turbine engine exit plane conditions were originally specified as follows:

	Idle	Military (Full Power)
Temperature	477°K (400°F)	922°K (1200°F)
Pressure	34-69 kPa	276-345 kPa
	(20-25 psia)	(55-65 psia)
Velocity	Mach 0.1	Mach 1.0-1.1
Particulate Mass Concentration	1-100 mg/m^3	
Particulate Mean Diameter	0.01-0.05 micrometers	
Particulate Size Range	0.005-1.0 micrometers	
Mixing Ratio	0.14-140.0 grams water/kg air	
(Absolute humidity)	(1-1000 grains water/lb air)	

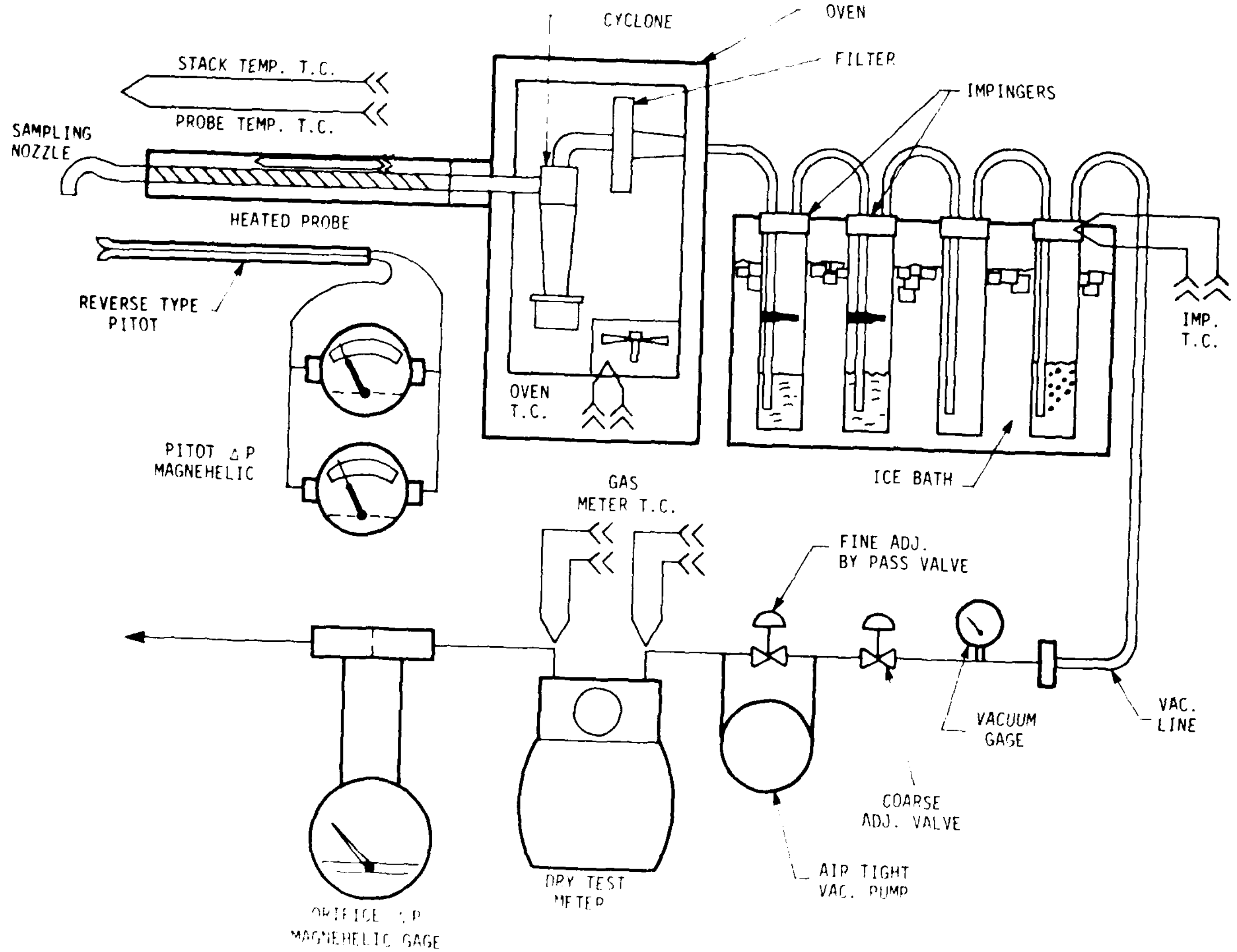


Figure 1. EPA Method 5 Particulate Sampler

As indicated, operation at sample gas temperatures of up to 922°K (1200°F) and velocities up to Mach 1.1 were originally required. Based upon data on the actual conditions at the exit plane of a J79-GE-17A engine, the specified operating conditions were changed to Mach 1.4.

The specifications required that the sampler be capable of measuring particulate mass loading and particulate size distributions in the exhaust stream of a gas turbine engine mounted in a test cell, a test stand, or a stationary airframe. It was further required that the sampler be capable of automatically detecting and maintaining isokinetic flow conditions throughout the sampling period.

A probe shutoff valve and bypass system was included so that sampling could be interrupted or discontinued while the engine is running.

In order to prevent water or SO_3 condensation in the filter, an oven capable of being heated up to 533°K (500°F) was required to house the filter.

The sampler was designed to minimize system size and weight and be positioned on conventional pallets for transporting.

A maximum sampling rate of 226 l/min (8 scfm) was specified. Particulate deposition was limited to less than 5 percent by weight in locations other than on designed collection surfaces.

The minimum number of parameters for which electrical outputs were required included all pressure measurements and temperature measurements for the probe and sample stack gas and flow measurement device inlets.

The control system was required to determine and maintain the isokinetic conditions within ± 10 percent and respond to a 10-percent change in velocity in less than one second in order to adequately track gas turbine engine operating transients.

Size distribution information for each 5-minute engine operating mode was required in the size range of 0.01 to 1 μm.

Provisions were later made to include a two-axis traversing stand, an automatic control system, a purge system, and additional testing and documentation.

All of the design goals were met on a qualitative basis. Further testing is planned by the Navy to confirm the range of sampler size distribution information capability and the ability of the sampler to maintain isokinetic conditions during gas turbine engine operating transients.

SYSTEM DESIGN

The system design was, in large part, determined by the requirement to follow the principle of the EPA Method 5 Sampler. A system block diagram of all major elements including the traverse and purge system is

shown in Figure 2. The principal differences between an EPA Method 5 sampler and the automatic isokinetic aircraft gas turbine particulate sampler are the inclusion of the sampling logic and control system, the automatic traverse capability, and the addition of the size distribution analyzer.

The system schematic is shown in Figure 3. The main functional elements are shown excluding the traverse subsystem and the control subsystem. Figures 4 and 5 show the equipment as constructed and tested. Figure 4 depicts the system on the fixed position support stand, and Figure 5 shows the system mounted on the two-axis traversing stand.

The system can be divided into the following main subsystems: mass sampling subsystem, size distribution analyzer subsystem, the traverse subsystem, and the control subsystem. These subsystems are discussed in the following paragraphs.

Mass Sampling Subsystem

The mass sampling subsystem consists of a sampling nozzle designed for subsonic and supersonic operation, a sampling probe with purge capability, a filter and oven, condenser, high volume sampling pump, and flow metering and flow control valves.

Sampling Nozzle

The sampling nozzle, designed for subsonic operation and supersonic operation up to Mach 1.4, was manufactured from Inconel alloy X-750®. to withstand the high temperature, stress, and noise environment. Figure 6 shows the sampling nozzle, pitot tube and probe subassembly. The sampling nozzle is shown to the left of the pitot tube in Figure 6.

Low speed isokinetic sampling requires that the sampling nozzle have a sharp edge in order to minimize particles being washed into the sampling stream and influencing the measurement. Particle buildup and the subsequent flaking-off into the sampling stream is also avoided. At supersonic flow conditions, the nozzle must be designed to allow the sampling stream to pass through the sampling nozzle opening into the sampling probe without choking. Isokinetic sampling is generally achieved by adjusting the aspiration rate through the sampling nozzle to be equal to the freestream flow per unit area. This is accomplished by adjusting the pressure downstream of the nozzle.

Figures 7 and 8 illustrate the operation of a sampling nozzle in subsonic and supersonic flow streams. At subsonic flow conditions, the captive streamlines can be altered ahead of the nozzle due to the presence of the nozzle. The conditions of flow rates above, at, and below the isokinetic flow rate are shown in Figure 7, where A_0 is the capture stream tube area and A_i is the nozzle inlet area. Even at the isokinetic flow rate condition, $A_0 = A_i$, it is known that some small alteration of the captive streamline shape may result from the presence of the sampling nozzle in the flow. These effects are small and

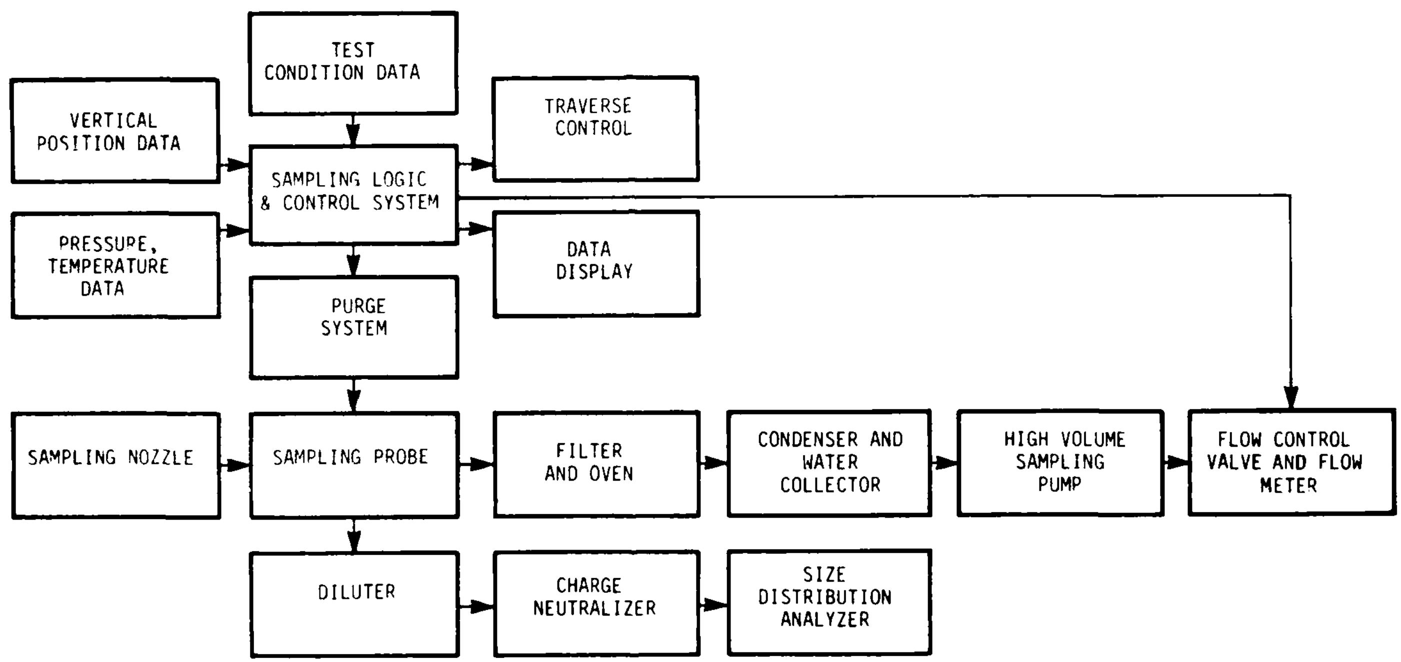


Figure 2. Block Diagram of Aircraft Engine Particulate Sampler

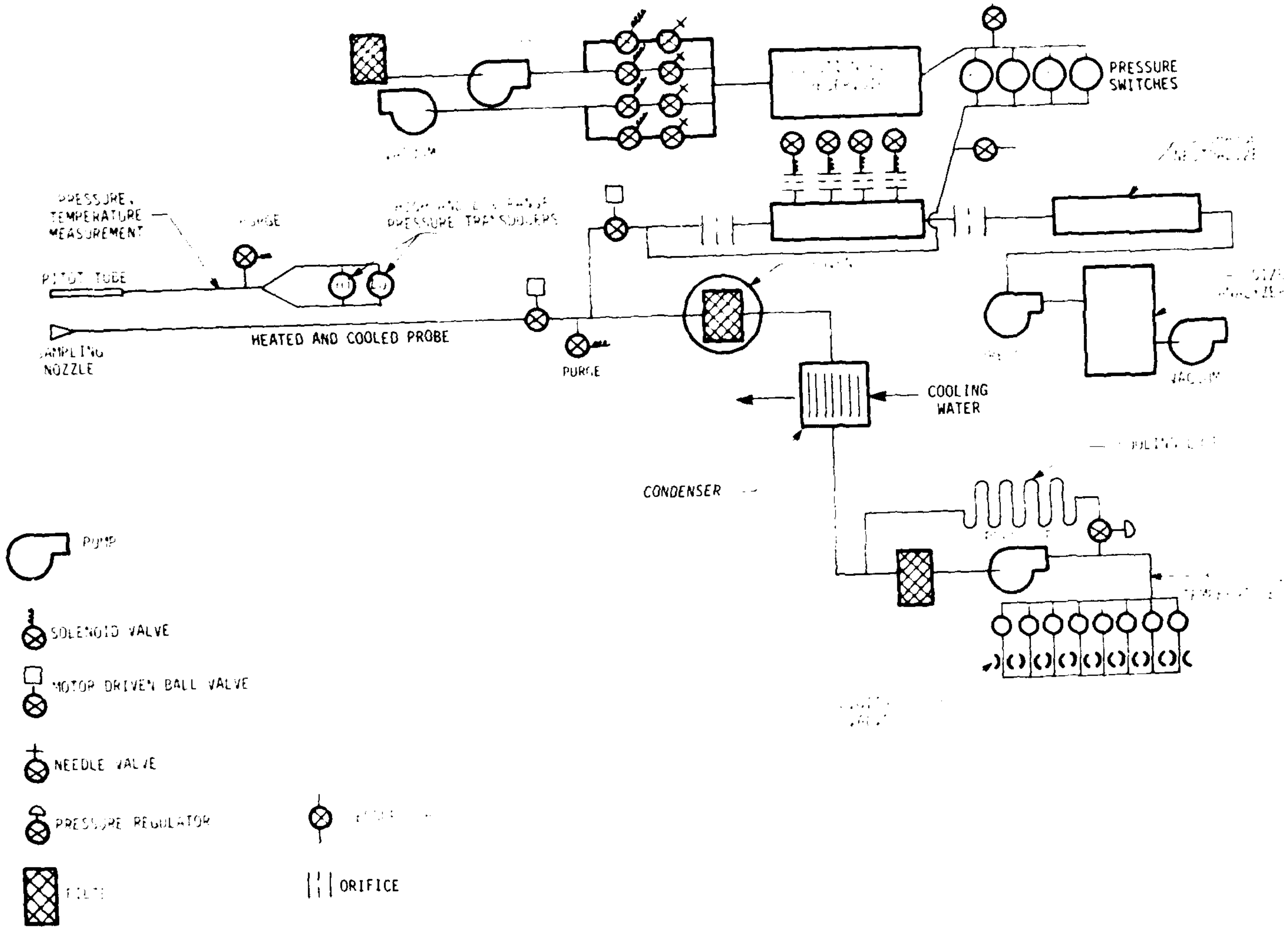


Figure 3. Schematic Diagram of Sampler

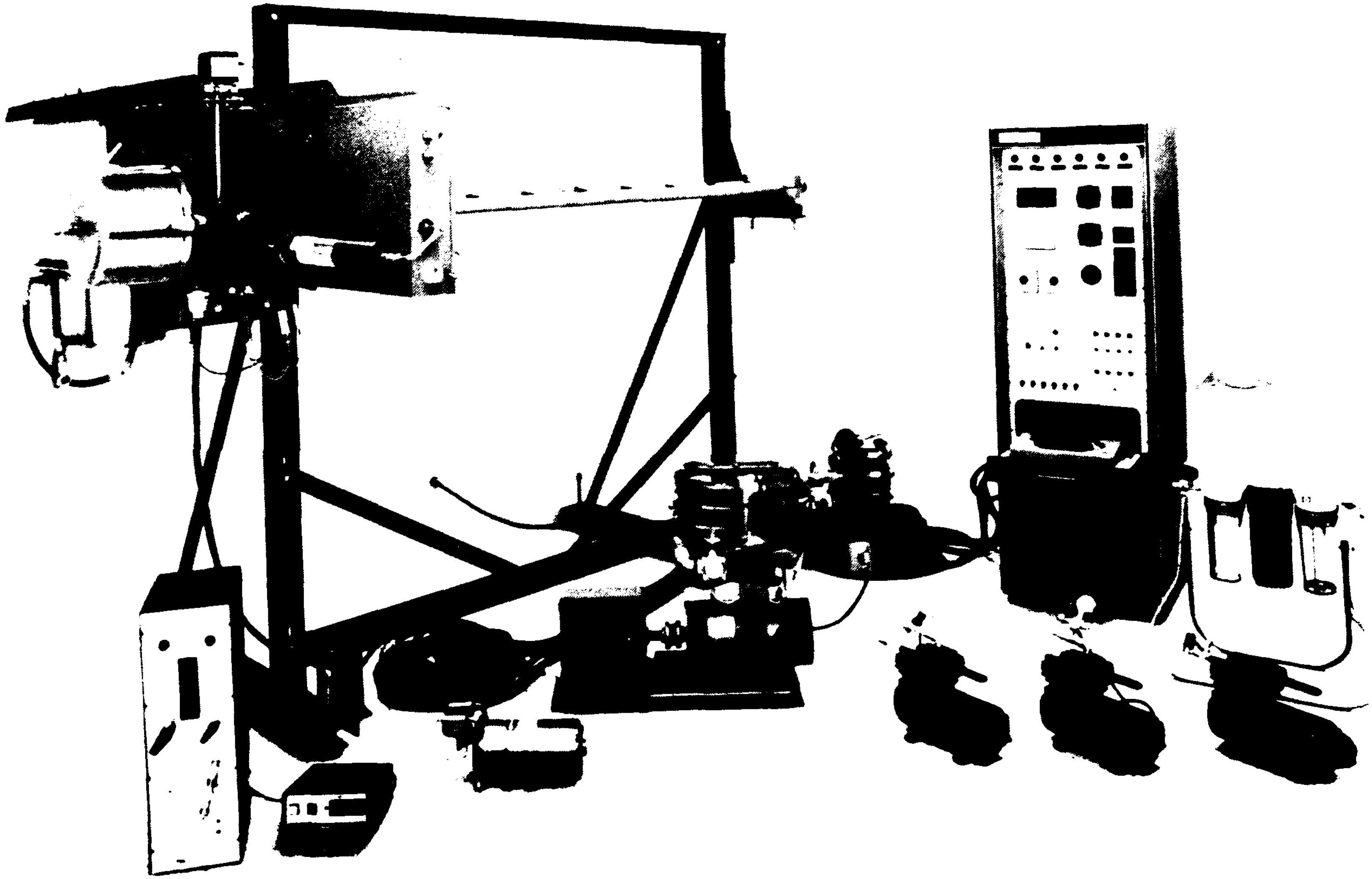


Figure 4. Sampler With Fixed Position Support Stand

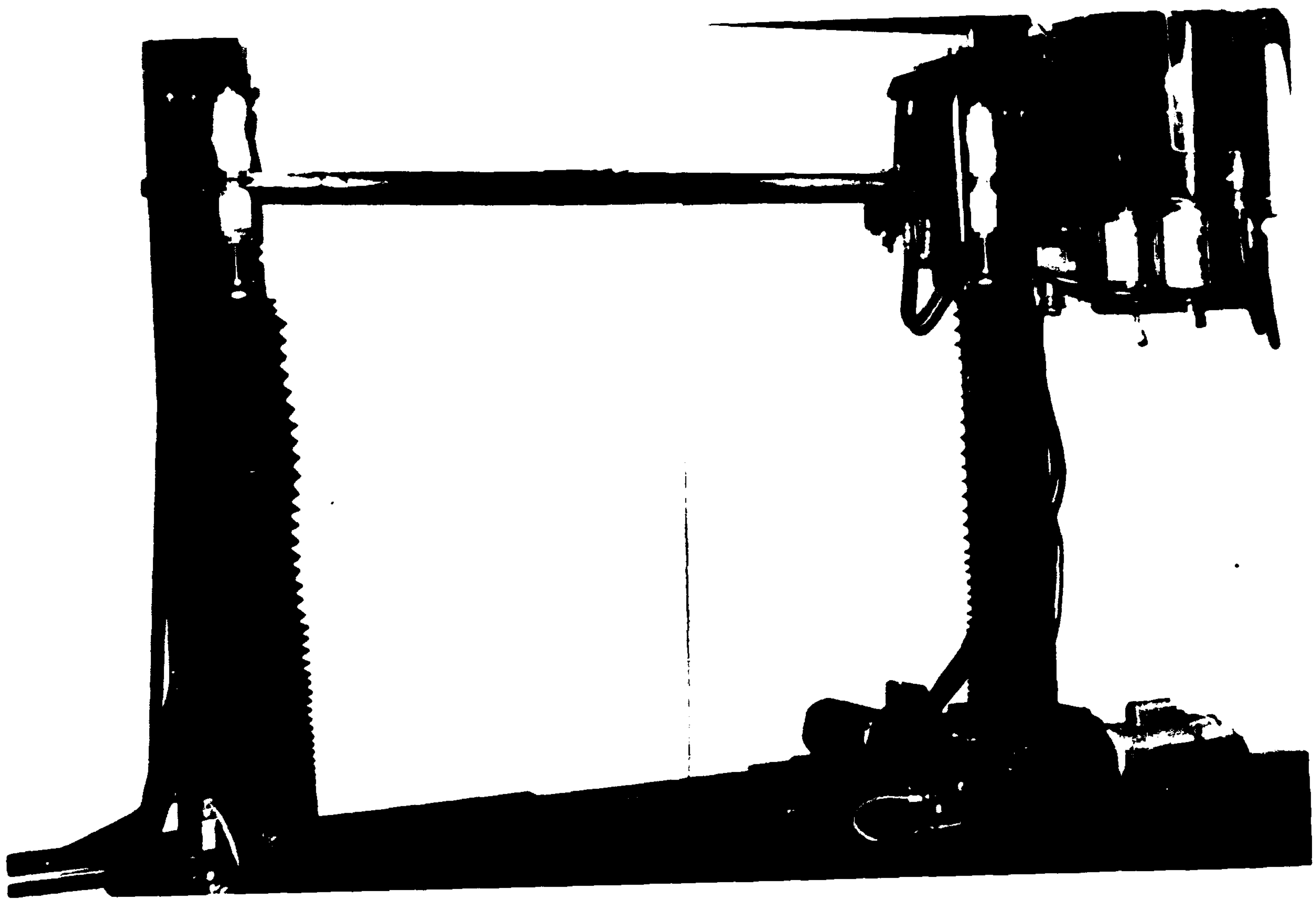


Figure 5. Sampler Mounted on Two-Axis Traversing Stand

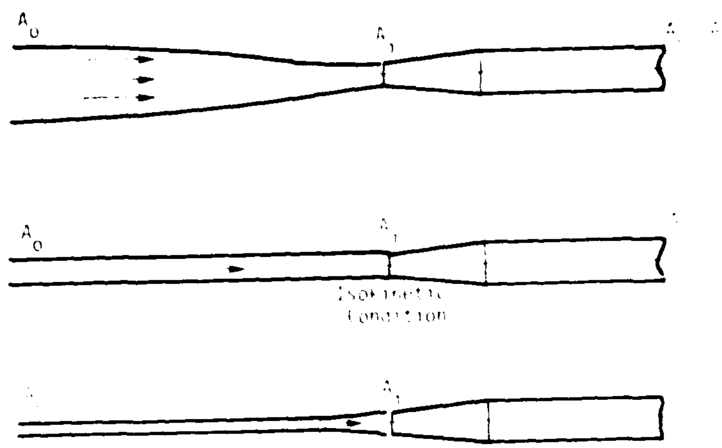


Figure 7. Subsonic Sampling Nozzle Operation

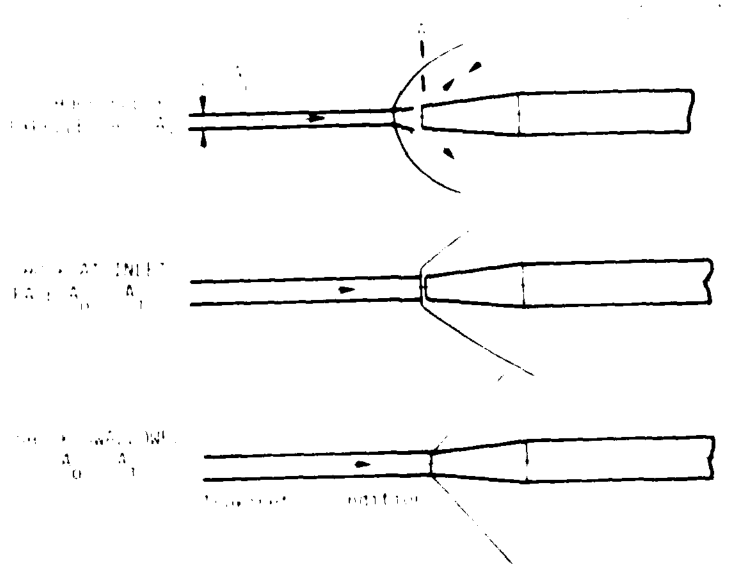


Figure 8. Supersonic Sampling Nozzle Operation

will not significantly alter the isokinetic conditions. For both subsonic and supersonic operation, the leading edge of the nozzle should be a knife edge and the external cone angle should be as small as possible.

Figure 8 illustrates the supersonic operation of the sampling nozzle. Three operational conditions are shown. When the aspiration rate is below the isokinetic rate, i.e., $A_0 < A_i$, a shock wave will appear ahead of the nozzle. This wave will cause a percentage of the flow to be deflected or spilled around the nozzle opening. This is the sole mechanism for flow spillage since the streamlines ahead of the shock are not affected by the presence of the nozzle. As the aspiration rate is increased toward the isokinetic rate, the shock will position itself right at the inlet. At this point, if the pressure in the nozzle is further reduced, the shock wave will become swallowed inside the nozzle and exact isokinetic conditions will result. This nozzle was sized for 226 l/min (8 scfm) at Mach 1.4; T = 944°K (1240°F) and P_T = 207.7 kPa (30.12 psia). For higher pressure environments, as experienced with the J79 engine, the maximum flow rate would be higher.

The internal configuration of the sampling nozzle was designed to optimize the pump requirements. Figure 9 depicts some aspects of an ideal nozzle designed for subsonic sampling and supersonic sampling at Mach 1.4. Sampling isokinetically at Mach 1.4 will result in a shock wave originating at the nozzle edge. This shock will be internal to the nozzle and will no longer remain planar. Instead, it will interact with the boundary layer inside the nozzle to form a "shock train." As shown, the internal flow should first be expanded to a somewhat higher Mach number. A sufficient entrance length with boundary layer tripping devices should be provided to stabilize the position of the front of the shock train. This entrance length should be about five nozzle diameters long. The shock train itself should not exceed 8 to 10 diameters and should be fully contained in a constant area passage. Since sonic conditions exist at the end of the shock train, the area here must be larger than that required for the maximum isokinetic flowrate to be measured.

Downstream of the throat, the subsonic flow is expanded to reduce the Mach number to a very low value (less than 0.1). This assures that if the flow must traverse additional piping, as in this case, constriction due to frictional choking is minimized.

The designed nozzle was subsequently used in a separate program by Martone (Reference 5), and its ability to sample isokinetically (i.e., swallow the shock) in cold flows was verified up to Mach 1.45. To withstand the high temperatures, Inconel alloy X-750® was the construction material specified.

In addition to the internal nozzle configuration, the mutual flow interference effects of the pitot tube and the sampling nozzle were minimized. This was accomplished by graphical layout of shock angles for various pitot tube-nozzle configurations and thereby estimating the best locations for shock generating edges. At subsonic speeds the presence of the sampling nozzle may affect the static pressure determination, and the presence of the pitot tube may affect the location of the capture stream

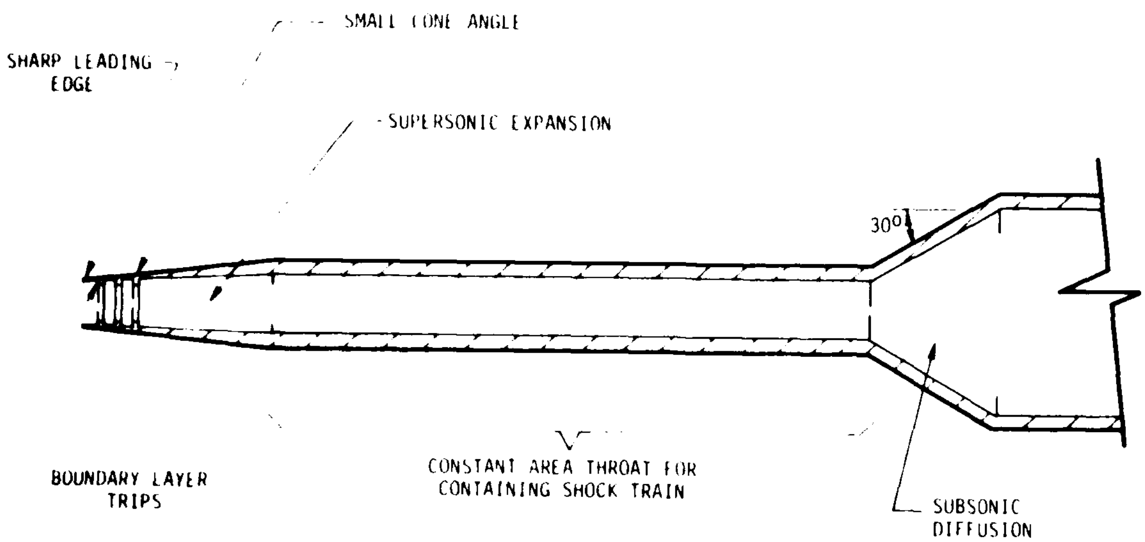


Figure 9. Sampling Nozzle Design Features for Supersonic Operation

tube entering the nozzle. Likewise, at supersonic speeds, the shockwave generated from the nozzle could impinge upon the pitot tube and cause an erroneous reading.

Sampling Probe

The sampling probe is the structure which contains the sampling tube and supports the nozzle and pitot tube in the exhaust stream at the appropriate exhaust plane coordinates. The sampling probe is also used to condition the sample to allow passage through the sampling filter material. A partial view of the sampling probe is shown in Figure 6. It consists of two stainless steel water-cooled pipe sections that have been joined by plates to form a truss to absorb the dynamic loads. The front pipe is protected in the flow stagnation area by a heat shield. The heat shield is slotted and is attached to the pipe in only a few locations to allow thermal expansion. The front pipe contains the sample tube that transports the flow sample to the filter. The wide range of operating conditions requires that the tube be heated at low sampling rates and cooled at high sampling rates. The minimum temperature set point of the sampling tube (up to 533°K, 500°F) can be selected at the control console. The sampling tube is electrically heated, and an outer sheath allows for water cooling. The sampling tube may be removed from the probe housing for cleaning. The sampling tube attaches to the probe shut-off valve to allow isolation of the filter from engine pulsations when the system is not operating. This valve is electrically operated from the control console.

Operation of the sampler verified that the cooling jacket and heater maintain the sample gas temperature within the operational limits of the fiber glass filter material. The structure of the sampling nozzle was specified as Type S30400 stainless steel.

Filter and Oven

Particulate samples are collected at the filter for mass measurement. The sample gas flows from the nozzle shut-off valve through additional tubing into the filter housing. The stainless steel housing holds standard 142 mm (5.6 in.) diameter flat fiber glass filters, which are commonly used in high volume stack sampling applications. Deposition of sample on the tube walls has been reduced by minimizing tube wall surface area. The filter is housed in an oven that can be heated to 533°K (500°F), ensuring that the filter remains dry.

Under certain conditions, particularly isokinetic sampling, positive gauge pressures may result inside the filter housing. The standard Acurex filter housing, designed for negative gauge pressures, required modification utilizing four positive clamp capscrews. The standard V-clamp design was replaced with a bolted design. The modified design also provided for lower inlet velocities to avoid high impingement velocities onto the filter material and possible puncture. The filter seal is made of Teflon®. In order to prevent leakage at the high operating temperatures, the seals should be replaced for every test.

Condenser

The EPA Method 5 condenser consists of a set of glass impingers in an ice bath. For this application, a condenser of higher capacity and ruggedness was required that would still allow the collection of condensate, provide for cleaning and keep contamination to a minimum. Therefore, a special shell-and-tube condenser placed downstream of the filter and oven assembly was constructed using Type S30400 stainless steel. The parallel water-cooled tube bundles reduce the gas temperature to approximately 300°K (80°F). The condensate is collected in containers and its volume is measured after each test to determine the actual moisture content of the exhaust stream relative to that which was assumed prior to the test. The dry gas flows from the condenser by means of a sampling hose to the high volume sampling pump.

High Volume Sampling Pump

The sample gas is moved through the mass sampling subsystem by a large rotary vane vacuum pump. It is driven by a 4 kW (3 hp) motor and delivers 1556 l/min (55 scfm) free flow capacity. Mounted on the pump are the pressure bypass valve, control valve, recirculation loop, digital control valve, and the electrical connection box.

Flow Metering and Flow Control Valve

The gas is metered and controlled on the pump discharge by a nine-orifice digital flow rate measurement valve controlled by an eight-bit parallel output signal. This valve uses sonic nozzles rather than sharp-edged orifices for flow metering.

The binary-sized nozzles provide for 0.39 percent, 0.78 percent, 1.56 percent, 3.12 percent, 6.25 percent, 12.5 percent, 25 percent, and 50 percent of total flow capacity. This combination of nozzles allows a turndown ratio of 256 to 1 for the valve. Each nozzle provides absolute pressure recoveries of up to 92 percent. For example, for an upstream pressure of 201 kPa (29.2 psia), sonic flow through the nozzle is assured as long as the downstream pressure is 181 to 185 kPa (26.3 to 26.9 psia) or less. The flow rate through the nozzles does not change for downstream pressures between 101 and 181 kPa (14.7 and 26.3 psia). Since the pressure recovery capabilities of this valve assure sonic flow, the flow rate through the sum of nozzles is calculated from the basic equation for sonic flow:

$$w = \frac{kP_1 a_e}{\sqrt{T_1}}$$

where

w = mass flow rate
k = a constant that is determined by the type of gas and flow conditions
P_1 = absolute inlet pressure
a_e = effective area of the nozzle(s)
T_1 = inlet gas absolute temperature

Since the flow is sonic, only upstream temperature and absolute pressure transducers are required to calculate flow rate.

The digital valve achieves sonic flow with an upstream pressure as low as 131 kPa (19 psia) and an atmospheric downstream pressure. In addition, it has a response time of a few milliseconds to the desired setpoint without overshoot or transients. The valve itself is actuated by nine solenoids driven by 24 to 28 VDC. Signals from the computer or A/D converter are amplified to the solenoid requirements by a digital driver. The valve was calibrated to provide flows up to 331 l/min (11.7 scfm) at 131 kPa and 294^{o}K (19 psia, 70^{o}F) thereby increasing the sampler capability to include alternate sampling nozzles with flow rate capabilities exceeding 226 l/min (8 scfm). It is the last element in the mass sampling subsystem.

The requirement for the valve to operate under positive pressure on the inlet required the vacuum pump to operate under suction. To provide a constant inlet pressure to the valve, a recirculation loop with cooling was installed on the pump and included a bypass pressure control valve.

Size Distribution Analyzer Subsystem

It was determined that, for the size range of interest, only one instrument was commercially available that could quickly and accurately measure size distributions. The instrument is a mobility analyzer produced by Thermo-Systems, Inc. It requires a certain aerosol concentration range in order to avoid saturating its sensors and needs a consistent temperature environment for reliable measurements.

The configuration was selected based on the following requirements: the instrument had to be placed in a suitable environment near the test cell to allow personnel to make adjustments; the aircraft gas turbine exhaust stream captured by means of the nozzle had to be conditioned to the appropriate aerosol concentration and temperature; the amount of sample withdrawn from the sampling stream had to be small in order to avoid influencing the main sample measurement significantly for all aircraft engine operating modes.

The configuration selected is shown in Figure 3. A sample is withdrawn from the main sampling stream and diluted. The diluted sample is passed through a charge neutralizer to limit the loss of aerosol during transport to the mobility analyzer. The instrument and auxiliary equipment can be calibrated for aerosol losses by sampling known stream conditions and correcting the test results by applying empirical factors determined by calibration tests. As shown in Figure 3, the size distribution analyzer subsystem consists of the following components: diluter, charge neutralizer, and size distribution analyzer. These components are discussed in the following paragraphs.

Diluter

The flow sample used to obtain a real-time particle size distribution is extracted from the main sample downstream of the motor-driven ball valve at the end of the sampling transport tube. The sample size is determined by the flow requirements of the size distribution analyzer. The sampling rate of this unit is 5 l/min (0.2 scfm). Since the mass concentration range necessary for the operation of this instrument is 6 to 6000 $\mu g/m^3$, and the expected range of particle concentrations in the gas turbine exhaust is 1 to 100 mg/m^3, a diluter was required.

Incremental dilution ratios are achievable by opening a series of binary-sized orifices in the diluter. The diluter design provides for an equalization of pressures between the nozzle and the mixing chamber within the diluter housing. This ensures that the flow rate through the diluter and, hence, the dilution ratio, are functions only of total orifice area and probe and mixing chamber temperature differences.

The design of the diluter was based on work performed by J. C. Guichard in France (Reference 6). The basic configuration is shown in Figure 10. The diluter allows dilution ratios of up to 300 to 1.

Charge Neutralizer

Downstream of the diluter system, the sample is passed through a Thermo Systems Model 3012 Aerosol Neutralizer®. This device neutralizes the electrostatic charges existing on the aerosol particles. The residence time in the device is sufficient to reduce the charge level on the aerosol particles to the Boltzmann equilibrium level. Cooper and Reist (Reference 7) have discussed the design of radioactive aerosol charge neutralizers in detail.

Size Distribution Analyzer

A specimen of the diluted, neutralized sample is pumped into the Thermo Systems Model 3030 Electrical Aerosol Analyzer® (EAA). This instrument measures the size distribution of particles contained in the sampled gas. Lundgren, et al (Reference 8) provides a thorough description of the EAA.

Traverse Subsystem

The basic sampler was designed and constructed with a fixed position support stand to allow initial checkout of the system. It was known that stratification of the mass concentration in the exhaust stream is likely due to placement of combustion chambers. Therefore, a two-axis traversing stand was added to the system.

The probe traverse subsystem consists of a rigid frame on which two orthogonally oriented screws are mounted. By adjusting the screws, the sampling nozzle is positioned within a 0.76 x 0.76-m (30 x 30-inch)

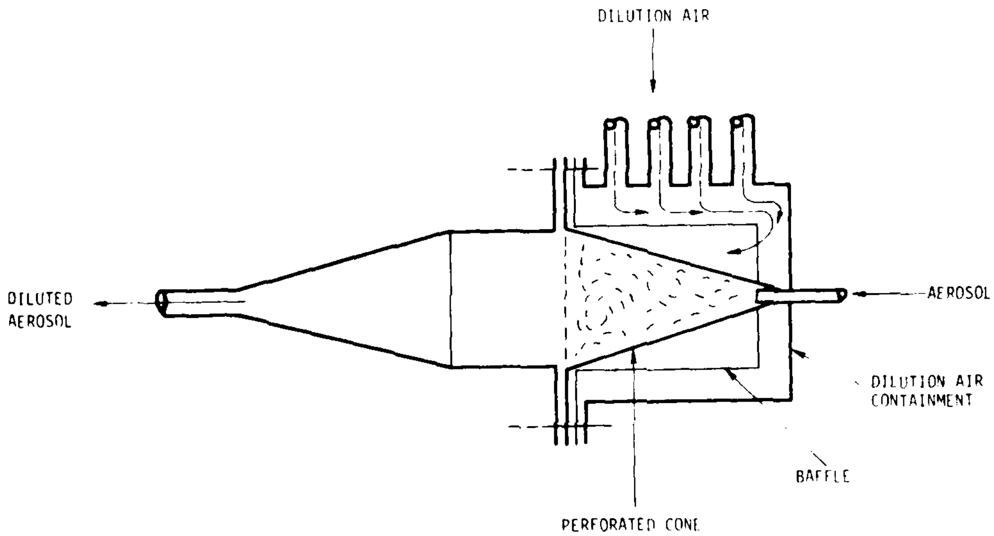


Figure 10. Diluter

area at the gas turbine exhaust plane. Each screw is provided with adjustable limit switches at each end. The position of the nozzle can be controlled either manually or automatically.

The traverse stand was required to stay clear of the aircraft gas turbine exhaust stream to minimize loading of the frame and minimize the effects of sampling on test cell operation. The largest engine exhaust diameter to be sampled was 76.2 cm (30 inches). The traverse system allows either manual or automatic remote operation and operates according to EPA Method 5 procedures or any other operator selected sampling matrix.

The probe was designed with the nozzle and pitot tube located in the center along its length. In order to traverse an engine exhaust plane of 76.2 cm (30 inches), the probe was designed to be more than twice this length.

The pressure force on the fully submerged nozzle was calculated to be equal to approximately 13.3 kN (3000 lbs_f). This large force, combined with the high temperatures and noise environment, required careful consideration in the design of the structure.

The structure was designed to interface with existing test cell designs. Test cells at the Naval Air Rework Facilities in Alameda and North Island were inspected to make the system as universal as possible. Small variations from one installation to another would necessitate minor modifications to the traverse system mounting. Some smaller test cells were found unsuitable. Since the test cells are grouped in pairs with one left- and one right-hand unit, umbilical lines of different lengths were required. To determine the suitability of the system for a test, considerations such as these must be evaluated on a case-by-case basis.

The traverse system was designed for both manual and automatic remote operation. Transducers mounted on the worm gear drives give the position information. The position can be read out at the control console in terms of percent of travel. Worm gear drives were selected over hydraulic actuators for this application due to their higher reliability in long term service.

Control Subsystem

The control subsystem includes flow measurement devices, manual and automatic controls, and data acquisition devices. The measurement of subsonic and supersonic flow with the same instruments places some stringent requirements on the control system. For example, the control system is required to select the computational procedure associated with either subsonic or supersonic flow. For supersonic sampling, calculation procedures are required to account for changes in flow variables across the shock wave. The following paragraphs describe the pitot tube, manual controls, and automatic controls and data acquisition.

Pitot Tube

The selection of the control subsystem configuration depends heavily on the pitot tube design. A standard 6.3-mm (1/4-in)-diameter

pitot tube was fabricated from Inconel alloy X-750® and equipped with a special collar for rigidity. A stagnation temperature measurement was also incorporated at the pitot tip. To eliminate the chance of fluctuations about the measurement point, a small dead band was introduced in the control logic. To extend the range of flow velocity measurement from engine idle to full power, two pressure transducers were used, one each for the high and low ranges.

Manual Controls

The manual control panel (Figure 11) provides for manual control and readout of key process parameters and traverse coordinates. Alarm indicators are provided at the top of the panel to indicate unsafe operating conditions and status data. These are: system purging, pump capacity exceeded, probe valve closed, low condenser coolant, and low coolant pressure in the sampling probe (two locations).

Temperature indicators are provided for gas turbine exhaust stagnation temperature, sampling tube temperature, oven temperature, condenser outlet temperature, control valve inlet temperature, aerosol diluter inlet temperature, and dilution air temperature. Additionally, temperature controllers are provided for the probe and oven.

Pressure indicators are provided as a percent of transducer range and include gas turbine exhaust stagnation pressure, control valve inlet pressure, high and low differential between gas turbine exhaust stagnation pressure, and static pressure.

The traverse position is indicated also as a percent of range on the same readout as the pressure measurement. Channel selector switches allow for switching from one measurement to another.

A manual control valve position selector is provided along with switches for the probe valve actuation, purge actuation, and traverse mechanism actuation. A separate panel is provided for the diluter.

Although the controls provided allow for manual operation, the computations required to determine isokinetic conditions are too complex to be computed at the time of the test. For example, for each test, a survey of gas turbine exhaust conditions has to be performed and set-point curves prepared. Consequently, automatic isokinetic control was incorporated in this system. The control strategy to be implemented called for selected manual start-up and shut-down controls and automatic operation for the sampling period.

Automatic Controls and Data Acquisition

The microcomputer is shown in Figure 12. Its interface boards condition the input and output signals to the microprocessor. Figure 13 shows the overall control system block diagram.

Sensor signals from temperature, pressure, and position measurements are conditioned with the A/D interface board. Temperature

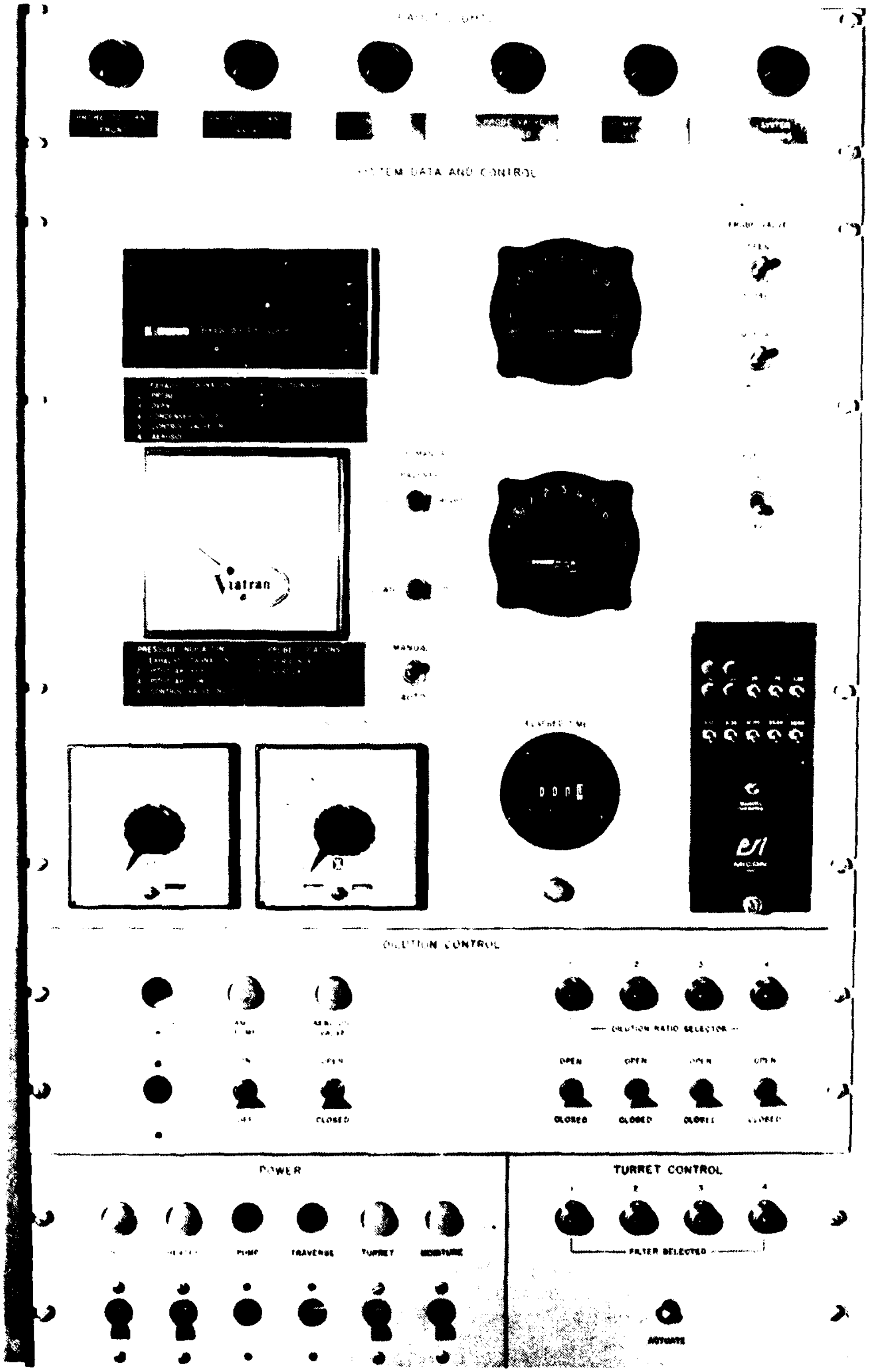


Figure 11. Manual Control Panel

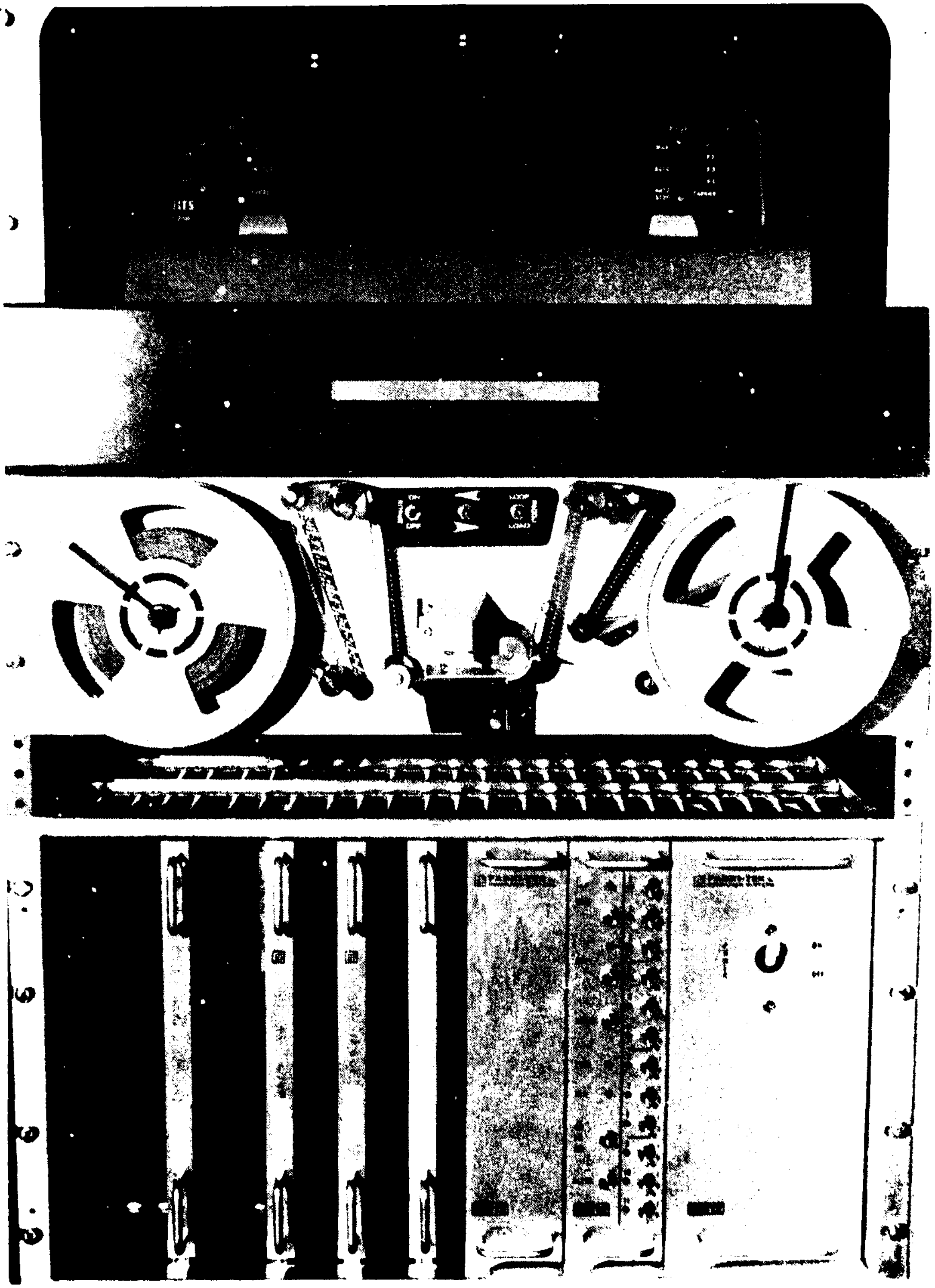


Figure 12. Microcomputer Control System

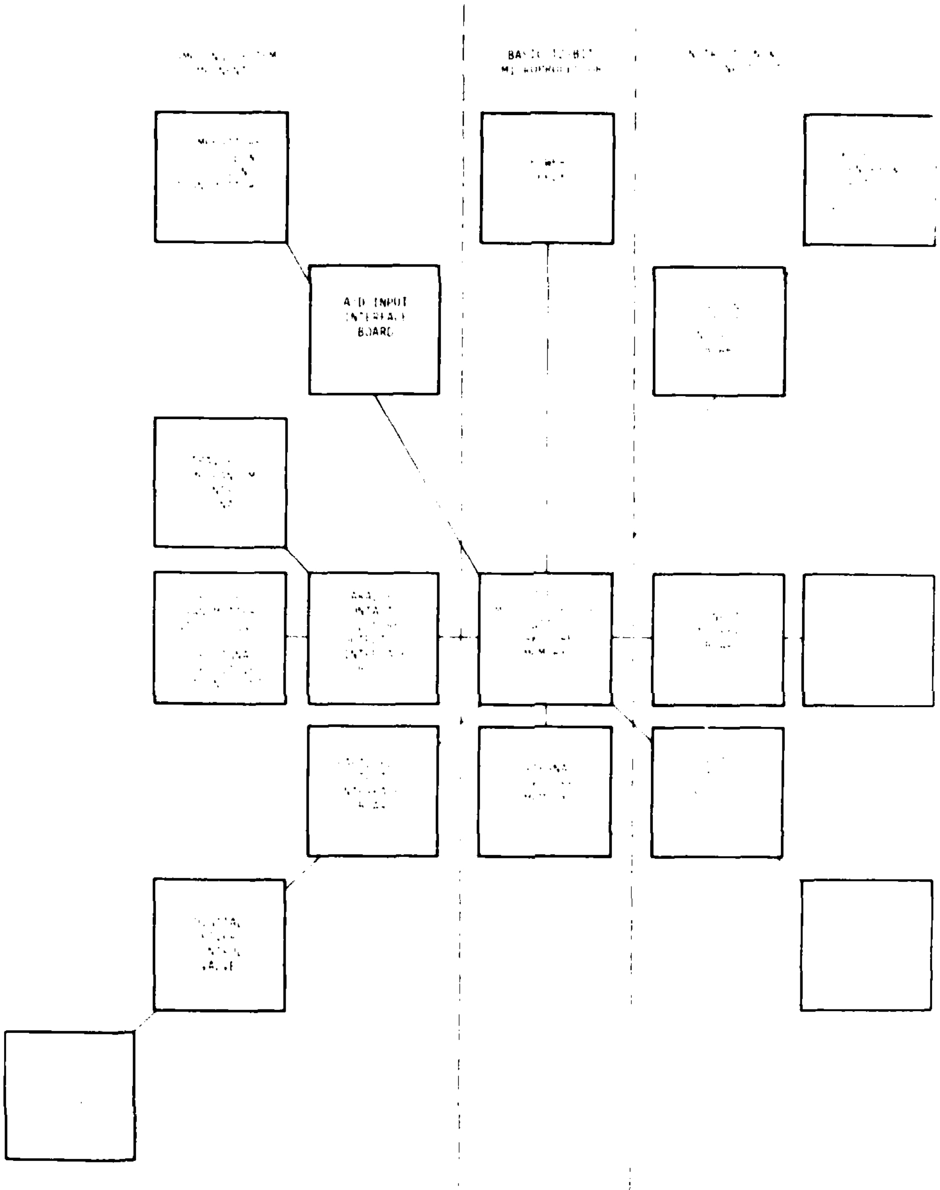


Figure 13. Control Subsystem Block Diagram

signals are 0 to 10 VDC and pressure signals 0 to 5 VDC. Position measurement signals are 0 to 10 VDC with gain adjustments as required.

Control signals from the microprocessor are routed by means of parallel output interface boards to the various components. The digital control valve is provided with 24 VDC binary signals from the output digital driver. All other output functions are accomplished by computer controlled contact closures.

Both analog and digital systems were evaluated for their suitability for this application. Since subsonic and supersonic operation require the implementation of different logic controls, a digital system was selected. A 12-bit microprocessor was chosen with interface capabilities that could meet the computational time requirements and had the flexibility to adapt to the sampler equipment. In order to maintain speed, the program was implemented in machine language.

Programming of the machine was first done by means of teletype. As this method proved to be time consuming, a tape reader and printer were added for higher speed operation and error detection.

CONSTRUCTION

The construction of the sampling system was carried out in two stages. The first stage of construction included the basic assembly of the sampler and the size distribution analyzer train on a fixed position support stand. The traverse capability, purge system and additional computer equipment were added in the second stage. Intermediate tests verified the operation of the sampler and exposed problems that could be reduced or eliminated.

SECTION III

TESTING

Equipment checkout and aircraft gas turbine tests for particulate concentration and size distribution measurements were conducted. Equipment checkout tests were performed as required to verify the function of components. In addition, logic tests were performed to ensure that the instruments provided the proper signals to the automatic isokinetic control system and that all other controls functioned properly. Two aircraft gas turbine tests were performed at the Naval Air Rework Facility, Alameda, California. Although the size data has to be considered preliminary and unconfirmed, the results suggest that the preponderance of turbine engine particles are submicrometer.

EQUIPMENT CHECKOUT

The equipment was checked for fit and function during construction. Few problems arose with the mass sampling train components other than some water leaks in the coolant circuits. The control equipment exhibited peculiar behaviors that were later traced to intermittent electrical failure in the microprocessor.

During checkout it was discovered that the power supply and the A/D interface boards were very sensitive to signal noise and input power voltage fluctuations, resulting in the loss of stored information in the core memory. Better shielding and an isolation transformer were installed to overcome these difficulties.

A leak test on the mass sampling system was performed on the system by capping the nozzle, opening the control valve, and evacuating the mass sampling train with the main pump. Note that when the pressure upstream of the control valve reads atmospheric pressure, the control valve should be closed and observed for pressure rise.

AIRCRAFT GAS TURBINE ENGINE TESTS

The first test was performed with the system under manual control. Installation of the sampler required approximately 1 day. The sampling equipment was located near the engine, and the control equipment was located in the center room of the cell complex adjacent to the control room. Umbilical lines were fed through a 15.2 x 15.2 cm (6 x 6-in) port through the 1.22-m (4-ft) thick wall.

On the third day a TF41 engine was tested and problems were identified. After 40 minutes of operation, it was determined that the engine had a seal failure, and no further tests could be conducted with this engine. Although a good sample was collected on the filter, no other engines were available to determine the effects of the sampler on engine performance. The filter was not torn and showed black particulate, including some metal flakes that appeared to have come out of the engine. A 280-mg (0.01-oz) sample was collected on the fiber glass filter during

the test run of 15 minutes at 75-percent power and 20 minutes at 100-percent power.

In addition to the mass sample, a real time particle size distribution measurement was made with the particle size analyzer train.

Some minor mass sampling train problems were noted that required repair. Of particular concern was the high vibration and noise environment which loosened some fasteners.

The second test was to show the proper operation and interface of the traverse mechanism with the test cell. Tests by several study groups were made at the same time to measure various pollution parameters and observe deposition of particulate on engine components. Included in the tests were measurements of opacity and hydrocarbon concentration. In addition, the effects of ferrocene addition on engine performance and hot section components were studied. EPA Method 5 tests were taken at the top of the cell stack. The traverse mechanism operated properly. The actual test samples were processed by Navy personnel.

The isokinetic aircraft gas turbine sampler was delivered to the Navy and checked out. Although a final complete test was scheduled, it has not been conducted as of the time of this writing due to schedule constraints.

SECTION IV

CONCLUSIONS

Conclusions drawn from the work described in this report result primarily from the experience gained in the unique sampling environment of aircraft engine test cells. Test cell size and configuration, as well as the severe operating conditions required several modifications to the EPA Method 5 sampling technique.

A universal system configuration for automated isokinetic sampling for particulate emissions from aircraft gas turbine engines is not practical, because of the wide range of test cell configurations. A basic system, however, can be designed and custom adapted for each cell with, in most cases, only minor modifications.

Because of the large test cell sampling envelope, traversing sampling is necessary in order to obtain representative exhaust stream samples. In addition, the basic test cell configuration requires long sample transport tubes for the particle size analyzer. This may introduce errors into the size distribution data. Calibration of the analyzer is recommended to determine the significance of line losses.

The severe noise environment in the test cell necessitates the incorporation of several design features. In order to assure a solid structural system during operation, locking fasteners were used for equipment support. Shielding of electronic equipment was required in order to minimize signal noise and power fluctuation.

For supersonic sampling, care must be taken in the placement of the pitot tube relative to the sampling nozzle in order to minimize mutual shock effects.

Finally, a system purge capability was included in order to keep contamination from initial startup after engine washdown out of the sampling system.

REFERENCES

1. "Standards of Performance for New Stationary Sources, Part II," Federal Register, 36(247), 24888-24890, December 23, 1971.

2. "1973 CRC Aircraft Engine Exhaust Particulate Measurement Tests," Coordinating Research Council Report No. 491, March 1977.

3. Champagne, D. L., "Standard Measurement of Aircraft Gas Turbine Engine Exhaust Smoke," ASME Paper 71-GT-88, March 1971.

4. Lapson, W. F. and H. Dehne, "The Development and Application of A High Volume Sampling Train for Particulate Measurements of Stationary Sources," Paper No. 74-189, presented at the 67th APCA Annual Meeting, Denver, Colorado, June 1974.

5. Martone, J. A., "Sampling of Submicrometer Particles Suspended in Near Sonic and Supersonic Free Jets of Air," Civil and Environmental Engineering Development Office, AD-A047829, CEEDO-TR-77-48, October 1977.

6. Guichard, J. C., "Construction et Etude d'Une Chambre a Dilution pour Aerosols," Institut National de Recherche Chimique Appliquee, Centre de Recherche 91710. Vert-le Petit, Note Interieure N^{O} 32-1966.

7. Cooper, D. W., and Reist, P. C., "Neutralizing Charged Aerosols with Radioactive Sources," Journal of Colloid and Interface Sci, Vol. 45, No. 1, October 1973.

8. Lundgren, D.A., et al, (editors), Aerosol Measurement, University of Florida Presses, Gainesville, FL, 1979.

INITIAL DISTRIBUTION

OSAD(I&L)EES	1
OUSDR&F	1
OUSDR&E	1
OSAF/MIQ	1
DTIC/DDA	2
ARPA	1
OSAF/PA	1
HQ USAF/LEEV	1
HQ USAF/LEEVP	1
HQ USAF/SGPA	1
HQ USAF/SGES	1
HQ USAF/LEEEV	1
AFMSC/SGPA	1
HQ AFSC/DLWM	1
HQ AFSC/DLFP	1
HQ AFSC/SGPA	1
AMD/RD	1
AMD/RDB	1
AMD/RDU	1
OEHL/CC	3
USAFSAM/EDE	2
USAFSAM/VNL	1
USAFSAM/CC	1
AEDC/DYR	1
AEDC/DDTR	1
AEDC/DOTR	1
AFOSR/CC	1
AFOSR/NC	1
HQ MAC/DEEV	1
HQ ATC/DEPV	1
OL-AD; USAF OEHL	1
HQ AFISC/SG	1
HQ AAC/DEV	1
USAF Hospital/SGB - Weisbaden	3
AUL/LSE 71-249	1
HQ USAFA/Library	1
AFRES/DE	1
Ch, Env Chem Div/USAEHA	1
Cmdr, USA Med Bioenergy R&D Lab	2
Ch, Industrial Hyg Div/USAEHA	2
USA. Chief R&D/EQ	1
USN, Chief, R&D/EQ	1
AFRPL/Library	1
AFRPL/LK	1
AFATL/DLODL (Tech Library)	1
AFWL/SUL (Tech Library)	1
AFTEC/SG	1
HQ SAC/DEPV	1
NCEL, L03B	1
Commandant/GDD	1
NASA Lewis Research Ctr (MS60-6)	1
FAA/AEE-300	1
FAA/ARD-550	1
EPA/SDSB	1
EPA/ORD	1
Env Res Lab/EPA	1
EPA/MD-46	1
EPA/ESRL	1
Library, Chemical Abstracts Svc	1
Toxic Matls Information Ctr	1
HQ AFESC/DEV	1
HQ AFESC/TST	1
HQ AFESC/RDV	10
AFFTC/CC	1
AFGL/LKD	1
Naval Air Propulsion Ctr	1
USA Environ Hygn Agency/ENGMC-RD	1
Federal Aviation Admin (AEQ-10)	1
USCG (G-WEP-1/73)	1
NEPSS/Naval Environ Spt Office	1
Pratt & Whitney Acft Corp	1
Pratt & Whitney Acft Group	1
Airesearch Manufacturing Co.	1
NAFES/ANA-420	1
Detroit Diesel Allison Div	1
AESO/Code 64240, NARF	3
Oregon State University	1
GE Electric Aircraft Engine Gp	1
AFWAL/POSF	1
AFWAL/POTC	1
AFWAL/THE	1
AFWAL/SFF	1
AFWAL/TBC	1
AFIT/Library	1
AFIT/DE	1
AFIT/DEM	1
ASD/YZEA	1
ASD/AEL	1
ASD/CC	1
ASD/DEP	1
FTD/LGM	1
HQ AFLC/DEPV	1
HQ AFLC/MAXF	1
Acurex Corporation	4

(The reverse of this page is blank)